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Heat treatment effect on thermo-mechanical fatigue and low cycle fatigue behaviors of A356.0 aluminum alloy

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ABSTRACT

In the present paper, the heat treatment effect on A356.0, a cast aluminum alloy which has been widely used in diesel engine cylinder heads, is investigated under out-of-phase thermo-mechanical fatigue and low cycle fatigue (at different temperatures) loadings. A typical heat treatment is applied to the material including 8 h solution at 535 °C, water quench and 3 h ageing at 180 °C. The experimental fatigue results show that the heat treatment process has considerable influence on mechanical and low cycle fatigue behaviors, especially at room temperature, but its effect on thermo-mechanical fatigue lifetime is not significant. The improvement in the strength can be explained by the dislocation theory. Under thermo-mechanical fatigue loadings, the difference between the fatigue lifetime of A356.0 alloy and A356.0-T6 alloy decreases when the temperature range increases. In this condition, plastic strain increases severely during the fatigue cycles in A356.0-T6 alloy due to over-ageing phenomenon and therefore, the amount of cyclic softening in heat treated alloy is more.

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1. Introduction

Aluminum alloy cylinder heads, as a part of combustion chamber, are required to meet two essential material properties. One of them is the resistance to deformations under combustion pressure and assembly loads. The second one is the toughness at high temperatures of the combustion flame to prevent cracking. These thermo-mechanical loading conditions can be handled by a combination of modern cooling methods or protective coatings. As an example, thermal barrier coatings lead to lower thermal stresses due to lower temperature gradient. Another example is to strengthen the material with a typical heat treatment process [1–3].

Several studies have been established for the fatigue behavior of aluminum–silicon alloys but less number of scientists investigated the effect of heat treatment. As an example, Takahashi and Sasaki [2] tried to show that an additional ageing process after T6 heat treatment was much more effective on low cycle thermal fatigue life of A356.0 aluminum alloy. As the alloys were aged longer and tempering enhanced, the fatigue lifetime lengthened.

A number of researchers proposed fracture mechanics of aluminum alloys, such as Caton et al. [4] who monitored the small-crack growth in Al–Si–Cu alloy for three different solidification times. Two conditions including peak-aged (T6) treatment and over-aged (T7) process were considered in this article. The fatigue behavior of aluminum foams was investigated at the macro- and micro-scales by Zhou and Soboyejo [5]. They compared the foams in various states including as-fabricated, annealed and T6-strengthened conditions. The effect of ageing treatments on the fatigue crack growth of 7010 aluminum alloy was studied by Desmukh et al. [6].

Some other researchers worked on the fatigue lifetime. Sadeler et al. [7] improved high cycle fatigue behavior of 2014 aluminum alloy by the heat treatment. Firouzdor et al. [8] investigated the effect of micro-structural constituents on the thermal fatigue life of A319 aluminum alloy. They showed that although T6 and T7 heat treatments appeared to be highly beneficial for the thermal fatigue performance, but T7 treatment could not improve the material performance more than T6 treatment. The effect of ageing time and temperature on fatigue and fracture behaviors of 6063 aluminum alloy was studied by Siddiqui et al. [9] under seawater conditions. They demonstrated that the increase in the fatigue resistance property with ageing time was linked with the vacancies assisted diffusion mechanism and also by the hindering of dislocation movement by impure atoms. AA7030 aluminum alloy was tested under low cycle fatigue loadings by Hoernqvist and Karlsson [10]. Their objectives were to determine the cyclic deformation

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properties and to investigate the influence of heat treatment. Their results showed that although the fatigue life is longer in the natural ageing temper at a given plastic strain amplitude, but also the fatigue life can be described by a total strain amplitude approach, where both natural ageing and peak ageing fall on the same straight line. Toda et al. [11] improved thermo-mechanical fatigue resistance of aluminum alloys with the age-hardening. They illustrated that applying out-of-phase thermo-mechanical treatment within small temperature and strain ranges prolonged in-phase thermo-mechanical fatigue life by 34%. The influence of heat treatment was evaluated by May et al. [12] for the fatigue lifetime of aluminum alloys. They demonstrated that the fatigue performance increased in 2024 alloy of about 34% just by using different age hardening, however, the diffusion phenomenon has made their surface very fragile, what led to the reduction in their lifespan.

According to the literatures review, studying the heat treatment effect on high temperature fatigue behavior of aluminum alloys is so rare, especially under thermo-mechanical fatigue loadings. Therefore, the objective of this work is to investigate out-of-phase thermo-mechanical fatigue (OP-TMF), room temperature (RT-) and high temperature (HT-) low cycle fatigue (LCF) behaviors of A356.0 aluminum alloy with and without the heat treatment. Therefore, experimental fatigue results are illustrated in graphical figures including the lifetime and stress–strain hysteresis loops.

2. Material

Mechanical and fatigue properties of a cast aluminum–silicon–magnesium alloy, A356.0 (Al–Si7–Mg0.3) is studied in the present paper. This aluminum alloy has been widely used in diesel engine cylinder heads. The chemical composition of the material includes 7.06% Si, 0.37% Mg, 0.15% Fe, 0.01% Cu, 0.02% Mn, 0.13% Ti and the remainder is aluminum. The production method is a gravity casting process in permanent molds. The initial microstructure of A356.0 alloy before fatigue tests is shown in Fig. 1 including as-cast state and with a typical T6 heat treatment. This picture consists of eutectic Al and Si particle phases. The dendrites (α -Al phase) can be observed with about 31.9 μm (as an average value) for the second dendrite arm spacing (SDAS). It should be noted that the heat treatment has no effect on SDAS [13].

A heat treatment process, entitled T6 is applied to the material including 8 h solution at 535 °C, water quench and 3 h ageing at 180 °C [14]. As mentioned in the literature, the ageing parameters (the temperature and the time) were optimized by Siddiqui et al. [9] for 6063 aluminum alloy under fatigue loadings. They concluded that the best precipitation hardening temperature is 180 °C when 6063 alloy is aged for 9 h and has achieved a maximum fatigue resistance property. But 3 h ageing has the highest lifetime for 6063 alloy when the ageing temperature increased. As another literature, Rometsch and Schaffer [15] presented an age hardening model for Al–Si7–Mg alloys. They showed that after about 5 h ageing (at 180 °C of ageing temperature), the hardness of A356.0 alloy will be maximized. Also, the cylinder heads manufacturers tend to reduce the ageing time to decrease the costs [16]. In such this case, the changes rechecked by the designer to have no major loss in the performance of cylinder heads under real TMF loading conditions. This typical heat treatment is considered for a passenger car with a diesel engine cylinder head made of A356.0 alloy [16].

The morphology of the microstructure changed obviously after the T6 heat treatment. As illustrated in Fig. 1, the solution treatment leads to the spheroidization of the eutectic silicon [17]. The irregular eutectic phase after the solution treatment is converted into fine spheroidized silicon particles uniformly distributed in the aluminum matrix [18]. Indeed, the T6 heat treatment provides

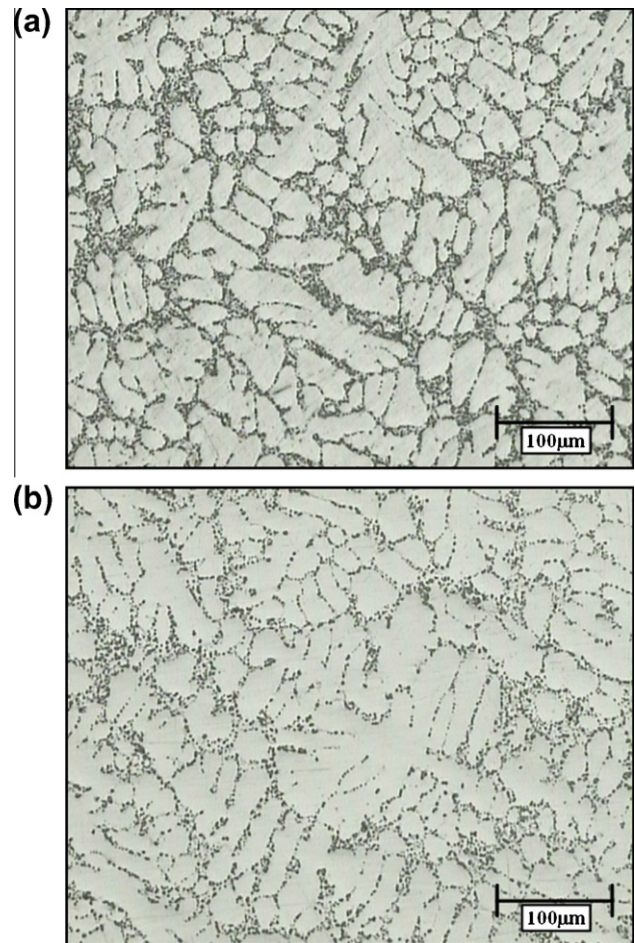


Fig. 1. The microstructure of A356.0 alloy before fatigue tests including (a) as-cast state and (b) with a typical T6 heat treatment.

two beneficial effects in Al–Si alloys. One is improvements in the ductility and the fracture toughness through the spheroidization of the eutectic silicon particles in the microstructure. The other is higher yield strength through the formation of a large number of fine β'' precipitates which strengthen the soft aluminum matrix. The first benefit is realized through the solution treatment while the second benefit is achieved through the combination of solution treatment, quenching and artificial ageing [19,20].

The hardness of A356.0 alloy is measured as 65 HB and 102 HB, before and after the heat treatment, respectively. Therefore, as expected, the heat treatment process increases the hardness and consequently, should increase mechanical properties, especially at room temperature [14]. The improvement of the tensile properties in the T6 heat treatment is directly related to the spheroidization of eutectic silicon particles and the precipitation of Mg_2Si particles during the ageing process [17].

3. Test conditions

In LCF tests, the temperature is constant during the lifetime and mechanical strain amplitude varies with triangular wave form between maximum and minimum values. This amplitude is set to 0.2, 0.3, 0.4 and 0.5% under the strain rate of 1%/s considering ASTM: E606 standard. TMF tests are carried out based on COP-EUR22281-EN procedure [21]. In OP-TMF tests, the temperature reaches to its maximum value, when the strain has a maximum compressive value and vice versa. This condition is comparable to start-stop cycles

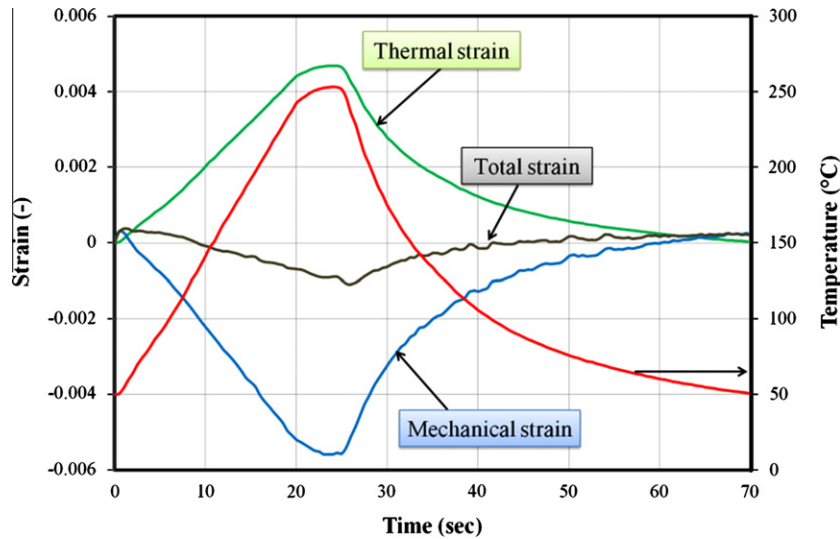


Fig. 2. The out-of-phase loading condition in TMF tests.

in engine cylinder heads. A typical out-of-phase loading condition of TMF tests is shown in Fig. 2. This figure shows the temperature and strains versus the time. The dwell time of 5 s. is considered at maximum temperature to reach the maximum value.

The details of TMF/LCF specimens are shown in Fig. 3 including the geometry and dimensions. As it can be seen, a hole with 1.5 mm diameter in the center of specimens is drilled. By using a K-type sheath thermocouple in this hole, the temperature is measured and controlled in TMF tests. Although 3 other thermocouples are used for measuring the surface temperature in TMF tests, but one thermocouple on LCF specimens is used to measure the surface temperature and control it in a constant value. This temperature is set to 25, 200 and 250 °C. TMF/LCF test equipments are shown in Fig. 4.

As shown in Fig. 4, for LCF tests, specimens are heated by an induction system and the temperature is kept in a constant value. In TMF tests, specimens are heated by the induction system where the temperature reaches to a maximum value such as 200, 225, 250 and 275 °C and then, the specimen is cooled down to 50 °C by a compressed air jet system. This heating/cooling rate is 10 °C/s in all experiments.

In TMF tests, a constraint factor or a thermo-mechanical loading factor (K_{TM}) which is presented in Eq. (1), is defined as a ratio of mechanical strain amplitude ($\epsilon_{a,mech}$) to thermal strain amplitude ($\epsilon_{a,th}$).

$$K_{TM} = \frac{\epsilon_{a,mech}}{\epsilon_{a,th}} = \frac{\epsilon_{mech}(T = T_{max}) - \epsilon_{mech}(T = T_{min})}{\alpha_{th}(T_{max} - T_{min})} \quad (1)$$

where α_{th} is the thermal expansion coefficient of the material. The value of K_{TM} remains constant as 125% during every TMF test. As an initial condition, tests begin with 0.03% of initial strain which can be compared with initial loadings in cylinder heads. This type of loadings can be created by bolt forces and the insert of valve seats. These OP-TMF loading configurations are set due to real operation conditions of cylinder heads [16,22,23].

It should be noted that all tests are performed under tension–compression loadings and the fatigue failure (the end of the lifetime) is defined as a first drop in maximum stress during the lifetime. Also, tensile tests are carried out with the same specimens under various temperatures such as 25, 150, 200 and 250 °C based on ASTM: E8 standard. In these tests, strain or stress can be controlled to compare their effects on mechanical properties of the material.

4. Results and discussions

In the first step, mechanical properties of A356.0 alloy, with and without the heat treatment are examined. The results of a simple tension test at different temperatures under strain-controlled or stress-controlled conditions are shown in Figs. 5 and 6, in comparison with Refs. [24,25]. These results show that there is no significant difference between strain-controlled and stress-controlled conditions. The values of elastic modulus and yield stress at room temperature are almost the same under strain-controlled and stress-controlled conditions. The value of ultimate stress under strain-controlled condition is slightly less than its value under stress-controlled condition.

It is obvious that by increasing the temperature, all mechanical properties of A356.0 alloy decrease. This reduction for ultimate stress is more than elastic modulus and yield stress. The value of ultimate stress at 250 °C decreases almost to the half of its amount at 25 °C for both un-heat treated and heat treated aluminum alloy. This behavior is a disadvantage for aluminum alloys which can cause the failures at high temperatures in cylinder heads. The value of ultimate stress for A356.0-T6 alloy is about 1.5 times more than A356.0 alloy. But the difference of ultimate stress between un-heat treated and heat treated A356.0 alloy decreases by increasing the temperature. It means that ultimate stress and yield stress in A356.0-T6 alloy have nonlinear behaviors with the temperature

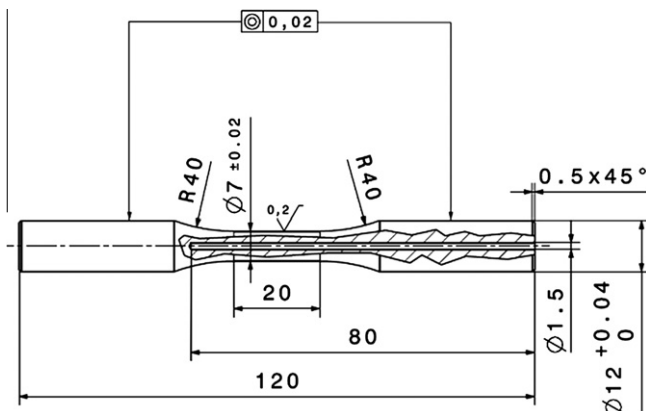


Fig. 3. The geometry of TMF/LCF specimens and their details (dimensions in mm).

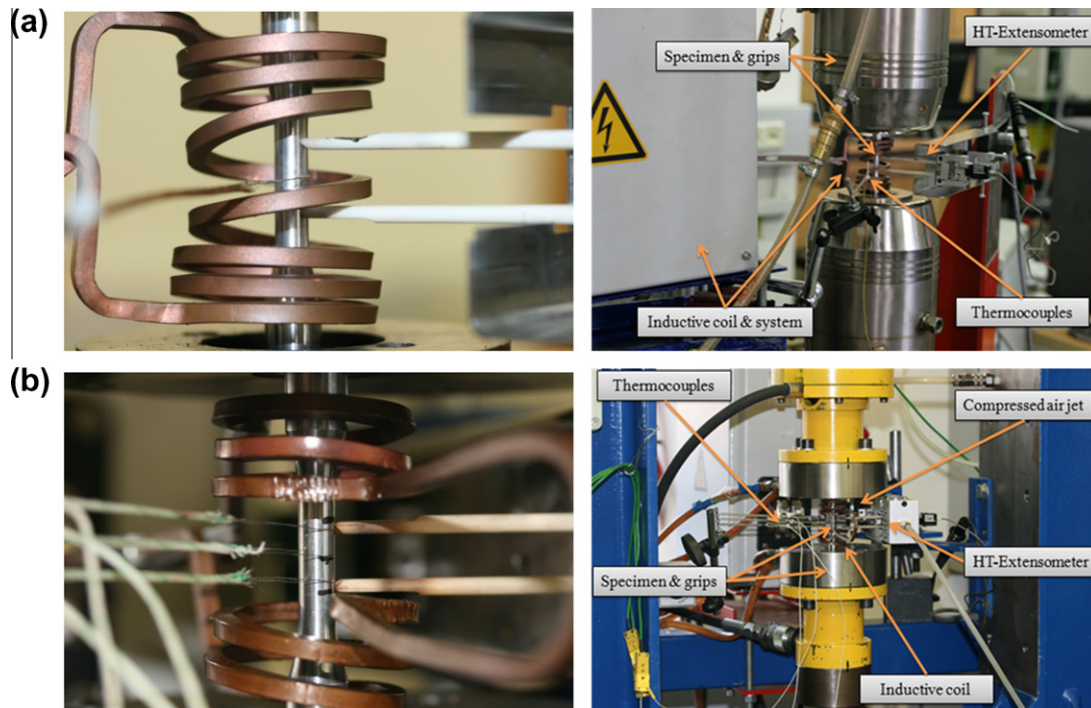


Fig. 4. The equipments for (a) LCF tests and (b) TMF tests.

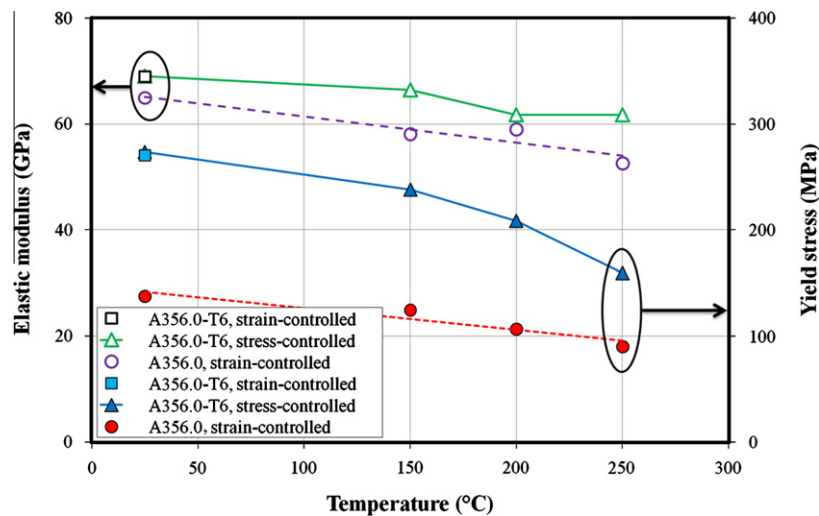


Fig. 5. The values of elastic modulus and yield stress versus the temperature.

and their reduction due to the temperature is more severe than un-heat treated A356.0 alloy (with a linear decreasing behavior as shown in Figs. 5 and 6). As a reason, the test temperature (especially more than 150 °C) overcomes the effect of ageing process which is performed at 180 °C. For further descriptions of this phenomenon, it can be noted that A356.0 alloy is strengthened by the precipitation of Mg_2Si [26], as also mentioned before [17]. After the heat treatment, the tensile strength increases which can be explained by the dislocation theory. All of the precipitates will dissolve into a single phase after the solution treatment. The subsequent quenching will form a supersaturated solid solution. This process will trap excess vacancies and dislocation loops. These lattice defects can later act as nucleation sites for precipitations. Due to high mobility of vacancies at room temperature as well as at high temperatures, Guinter Preston (GP) zones are produced which are very rich in Mg and Si atoms. The density of the GP zones

increases and heterogeneous precipitation of Mg_2Si occurs at ageing temperature above the GP zone solvus temperature which is about 147 °C [26]. These fine particles/clusters will pin dislocations and strengthen the material for under-aged to peak-aged temperatures. As the temperature increases (more than peak-aged temperature which is about 180 °C), the fine particles grow and coalesce which leads to reduce their pinning effectiveness, and thereby the strength decreases [9,18,26–28]. Chan et al. [26] reported that the dissolution of Mg_2Si may take place at the temperatures over 300 °C and so that the softening of A356.0 alloy and the recovery of the ductility may occur in solution-treated, natural-aged and peak-aged alloys.

In Fig. 7, mechanical strain amplitudes (including total strain and plastic strain, measured at the mid-life cycle) are demonstrated versus the fatigue lifetime (in the number of cycles) at various OP-TMF conditions. As expected, the TMF lifetime decreases

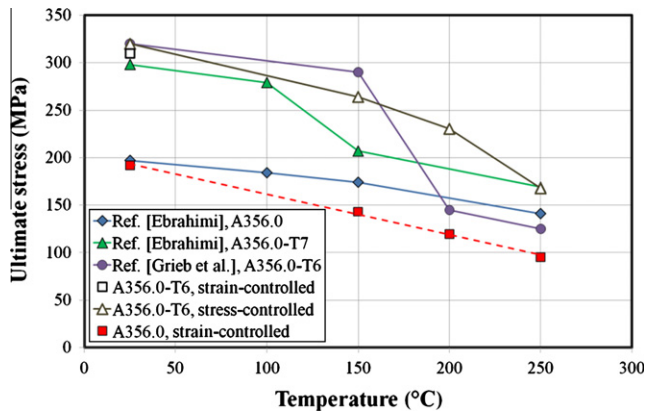


Fig. 6. The value of ultimate stress versus the temperature.

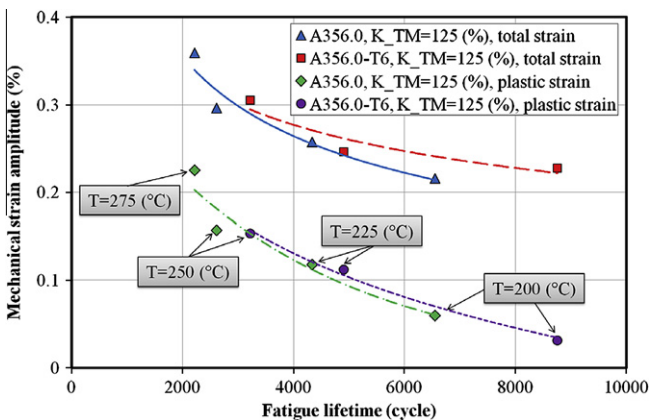


Fig. 7. The values of mechanical strain amplitudes (at the mid-life cycle), total strain and plastic strain versus the TMF lifetime for various maximum temperatures.

by increasing total strain amplitude due to increase in maximum temperature. The values of plastic strain (at the mid-life cycle) for A356.0 alloy and A356.0-T6 alloy are almost the same, although their TMF lifetimes are different.

The heat treatment causes 23% (as an average value) of the fatigue life improvement, but the influence is not significant. That is due to ageing effects during the lifetime under TMF loadings. After some cycles (about 1000 cycles), the behavior of maximum stress becomes equal for un-heat treated and heat treated A356.0 alloy, as shown in Fig. 8. In this figure, the temperature varies from 50 to 250 °C. This phenomenon means that the transient temperature (50 to 250 °C) overcomes the ageing effects (performed at 180 °C) in the heat treatment process. The reason is due to changes in the material microstructure which is exposed to the temperature, higher than the ageing temperature. According to the literatures, these micro-structural changes can be caused by the over-ageing in A356.0-T6 alloy which leads to a significant reduction of the strength (shown in Fig. 6) and therefore, increases the cyclic plastic deformation during TMF cycles [27]. This over-ageing phenomenon can be more pronounced at higher temperatures, higher dwell times and lower strain rates [27,28] where solute atoms have opportunities to precipitate in the aluminum matrix. It should be mentioned that the strain rate in TMF loadings is about 10^{-4} per second which can be one of the lowest achievable strain rates in the fatigue testing. In these conditions, the potential for the cyclic softening is more due to the over-ageing in heat treated aluminum alloys [28].

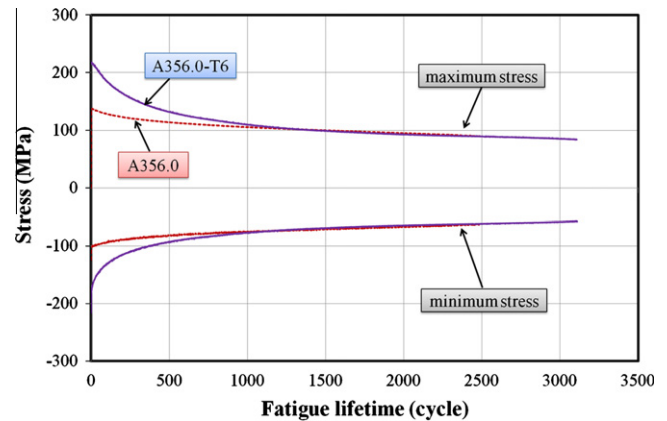


Fig. 8. The values of maximum stress and minimum stress during the TMF lifetime at 250 °C of maximum temperature.

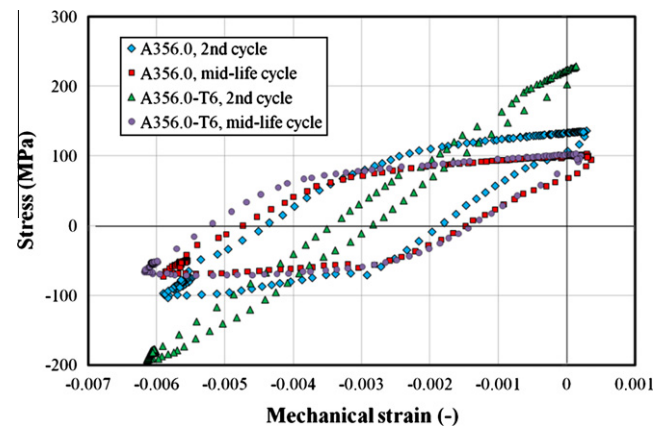


Fig. 9. The stress-strain hysteresis loops during the TMF lifetime at 250 °C of maximum temperature.

Stress–strain hysteresis loops for the second cycle and the mid-life cycle are illustrated in Fig. 9. This figure shows that A356.0-T6 alloy withstands higher values of stress and lower values of plastic strain (measured as the width of hysteresis loops at zero mean stress line) in the first TMF cycles. After some TMF cycles, for example, at the mid-life cycle, stress decreases and plastic strain increased due to over-ageing phenomenon [27]. This cyclic softening behavior is caused by the heat treatment effects on the microstructure of the material. Another note is about the amount of cyclic softening in A356.0-T6 alloy which is more than A356.0 alloy, as described before [28]. Therefore, plastic strain increases severely during TMF cycles, as shown in Fig. 10. For A356.0-T6 alloy, the plastic strain in the first TMF cycles is lower than A356.0 alloy. It means that the heat treatment reduces the ductility and the material behaves in a brittle manner [14]. This behavior can be observed in the hysteresis loops (shown in Fig. 9). After some TMF cycles (about 1000 cycles), the over-ageing leads to higher plastic strains, even more than A356.0 alloy. And thus, the cyclic behavior (stress–strain hysteresis loops) of A356.0 alloy and A356.0-T6 alloy becomes almost similar (according to the values of stress and plastic strain) at the mid-life cycle. This behavior can be also observed in the values of plastic strains which are shown in Fig. 7.

Figs. 8–10 show the experimental fatigue results at 250 °C of maximum temperature. The reduction in the value of maximum stress (during the TMF lifetime) decreases at lower maximum temperatures such as 200 °C. Thus, the difference between the TMF lifetimes of A356.0 alloy and A356.0-T6 alloy becomes more, as

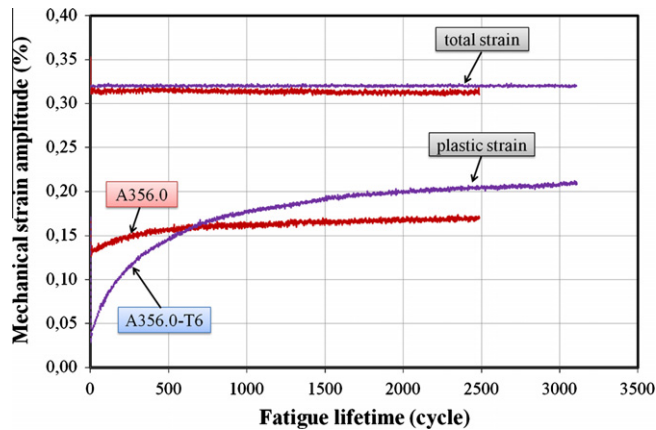


Fig. 10. The values of mechanical strain amplitudes, total strain and plastic strain during the TMF lifetime at 250 °C of maximum temperature.

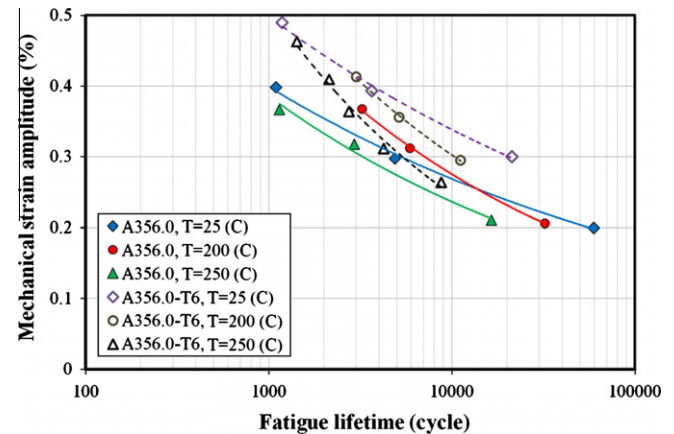


Fig. 12. The value of mechanical strain amplitude (at the mid-life cycle) versus the LCF lifetime.

shown in Fig. 11. In this case, the fatigue lifetime is improved as 34% by the heat treatment. At higher maximum temperatures (250 °C), this fatigue life improvement becomes about 13% by the heat treatment. This means that the fatigue life improvement decreases when maximum temperature increases. The reason is that maximum temperature becomes more effective on the material with the heat treatment and consequently, the amount of ageing during the TMF lifetime increases.

The results of RT-LCF and HT-LCF tests including mechanical strain amplitude (including total strain amplitude measured at the mid-life cycle) versus the fatigue lifetime are shown in Fig. 12. In all the cases, the LCF lifetime increases by the heat treatment process. For A356.0-T6 alloy, the fatigue lifetime decreases by increasing the temperature. But in A356.0 alloy (without the heat treatment), the LCF lifetime at 200 °C is more than room temperature due to micro-structural changes in the material [29]. Then, the lifetime decreases at 250 °C in comparison with room temperature. At lower mechanical strain amplitudes, this behavior is almost different due to high cycle fatigue region where stress controls the fatigue failure.

In all LCF tests, the heat treatment effect on the lifetime of A356.0 alloy is significant, especially at room temperature. It means that the LCF lifetime improvement in room temperature is more than the improvement in high temperatures (200 and 250 °C). At high temperature (250 °C), the cyclic behavior of A356.0 alloy and A356.0-T6 alloy at the mid-life cycle of LCF loadings is shown in Fig. 13. As demonstrated, a higher value of stress

occurs in heat treated aluminum alloy. But the value of plastic strain in A356.0-T6 alloy is less than un-heat treated aluminum alloy. The reason is that the heat treatment process (such as T6) hardens and strengthens the material and reduces the ductility [14]. Therefore, the value of plastic strain decreases in heat treated aluminum alloy (shown in Fig. 13), although the stress range of A356.0 and A356.0-T6 alloys are the same.

As an important outcome of this work, the fatigue lifetime improves by the heat treatment but the amount of improvements is not significant under TMF loadings due to over-ageing phenomenon. This over-ageing will be more effective in cylinder heads when the dwell time (in which the maximum temperature is held through the engine working) increases in real TMF loadings [27]. Therefore, the design process of cylinder heads, if the TMF behavior is only considered as the objective, the heat treatment can be eliminated. Because after some start-stop cycles in engine cylinder heads, the cyclic behavior of heat treated and un-heat treated aluminum alloy becomes almost the same. It should be mentioned that the heat treatment process requires times and costs in a production line of cylinder heads. One way to reduce the costs is to use local heat treatments or case hardening process (to strengthen and harden the surface) in cylinder heads. The examples of such these areas are cylinder head bolts and crank shaft bearings, where high plastic deformation occurs. Finally, micro-structural observations will be required to discuss about the phase changes in the material before and after TMF/LCF tests. These investigations will appear in the next other papers.

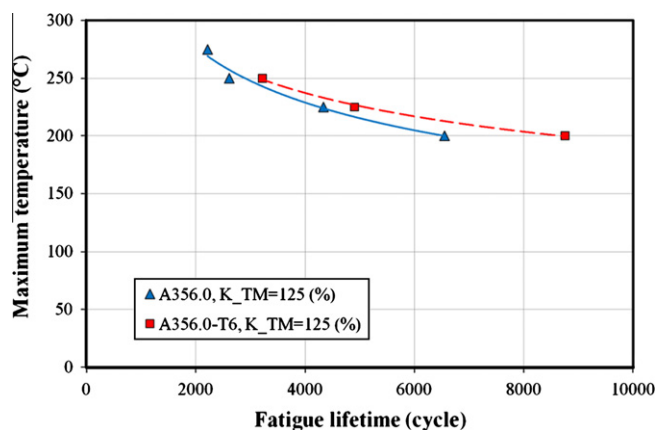


Fig. 11. The value of maximum temperature versus the TMF lifetime.

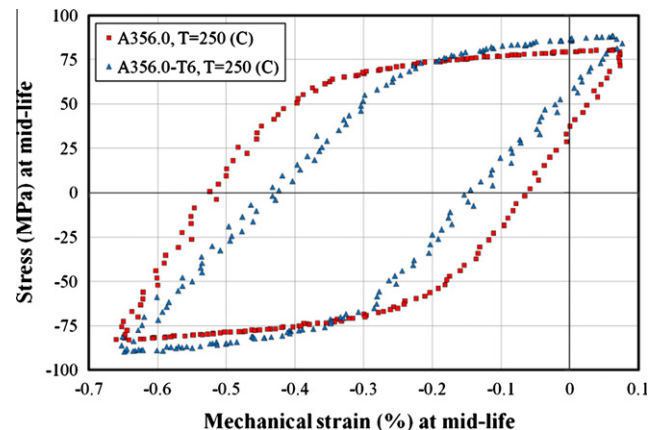


Fig. 13. The stress–strain hysteresis loop (at the mid-life cycle) for HT-LCF tests.

5. Conclusion

In this study, TMF, RT-LCF and HT-LCF behaviors of heat treated and un-heat treated A356.0 aluminum alloy are investigated with following experimental fatigue results.

- Mechanical properties and LCF behaviors (at various temperatures) of A356.0 aluminum alloy improves by the heat treatment, T6, especially at room temperature where its effect is considerable.
- The heat treatment has no significant effect on A356.0 alloy under TMF loadings. By increasing the temperature range, the difference between the fatigue lifetime of A356.0 alloy and A356.0-T6 alloy decreases.
- The amount of cyclic softening in A356.0-T6 alloy is more than A356.0 alloy and thus, plastic strain increases severely during the TMF lifetime of A356.0-T6 alloy due to over-ageing phenomenon. In LCF tests, plastic strain of A356.0-T6 alloy is less than A356.0 alloy due to lower ductility which is created by the heat treatment.

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